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Soft Body Simulation for the Fitting of Protective Equipment

Phase 2 Female-Specific Analysis

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PSPC Contract Number: W7719-205487/TOR/001
Technical Authorities: Linda Bossi and Allan Keefe, Defence Scientists
Contractor's date of publication: March 2021

Defence Research and Development Canada

Contract Report
DRDC-RDDC-2022-C056
February 2022

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IMPORTANT INFORMATIVE STATEMENTS

Soft Body Simulation for the Fitting of Protective Equipment

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TA1 Report for W7719-205487/TOR/001

Vital Mechanics Research, Inc.

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Soft Body Simulation For The Fitting Of Protective Equipment – Phase 2 Female-Specific Analysis

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Final Report for Task Authorization of Contract W7719-205487/TOR/001
March 31, 2021

Abstract

Aims: The primary aim was to evaluate the use of soft tissue models to assess the fit of protective clothing and equipment on female CAF personnel. Additional aims were to construct the soft tissue models from raw 3D scans provided by DRDC, and to assess fit in operational postures.

Outcomes:

Effectiveness of soft avatars. The results demonstrated more realistic predictions of fit using VitalFit soft avatars compared to hard avatars. Soft tissue compression in the breast and hip regions produced significant differences in airgap and peak pressures. In an earlier part of this study, we also showed that these differences are greater for female bodies compared to male bodies.

Implications for female body armour: The study showed some surprising consequences for changes in air gap and peak pressure with changes in strap tightness and posture for female personnel. Strap tightness decreased airgap and also peak pressure, but not uniformly. Peak pressures were observed on the shoulder and not on the breast, even on the female body, in our simulations. The location of high-pressure areas on the body varied with posture, with larger pressures observed on the hip and lower back during sitting and in the armscye areas during shooting. These pressures could lead to discomfort, distraction, and could limit the range of motion. Such results may be used to evaluate protection, as well as physical and thermal comfort, of female body armour.

Demonstration of Technical Capabilities: (1) Robust construction of soft avatars from raw scans, even in the presence of significant scanning artifacts. (2) Posable soft avatars. We demonstrated the capability to pose and register the avatar, including the soft tissue FEM model, in three operational postures: standing, sitting as in the back of a troop carrier, and holding the arms up in a shooting pose. These results suggest that it is possible to utilize 3D body scanning of CAF personnel to assess fit with soft avatars in operational postures, and suggest several avenues for further research.

Résumé

Objectifs: L'objectif principal était d'évaluer l'utilisation de modèles de tissus mous pour évaluer l'ajustement des vêtements et de l'équipement de protection sur le personnel féminin des FAC. Les autres objectifs étaient de construire les modèles de tissus mous à partir de scans 3D bruts fournis par RDDC et d'évaluer l'adéquation aux postures opérationnelles.

Résultats:

Implications pour les gilets pare-balles féminins: l'étude a montré des conséquences surprenantes pour les changements d'entrefer et de pression maximale avec des changements dans le serrage des sangles et la posture du personnel féminin. L'étanchéité de la sangle a diminué l'entrefer et également la pression maximale, mais pas de manière uniforme. Des pics de pression ont été observés sur l'épaule et non sur la poitrine, même sur le corps féminin, dans nos simulations. L'emplacement des zones de haute pression sur le corps variait selon la posture, avec des pressions plus importantes observées sur la hanche et le bas du dos pendant la position assise et dans les zones des bras pendant le tir. Ces pressions pourraient entraîner une gêne, une distraction et pourraient limiter l'amplitude des mouvements. Ces résultats peuvent être utilisés pour évaluer la protection, ainsi que le confort physique et thermique, des gilets pare-balles féminins.
Démonstration des capacités techniques: (1) Construction robuste d'avatars logiciels à partir de scans bruts, même en présence d'artefacts de scan importants. (2) Avatars souples posables. Nous avons démontré la capacité de poser et d'enregistrer l'avatar, y compris le modèle FEM des tissus mous, dans trois postures opérationnelles : debout, assis comme à l'arrière d'un transporteur de troupes et tenant les bras levés dans une pose de tir. Ces résultats suggèrent qu'il est possible d'utiliser la numérisation 3D du corps du personnel des FAC pour évaluer l'adéquation avec des avatars souples dans des postures opérationnelles, et suggèrent plusieurs pistes de recherché.

Project Overview

The overall objective of the project was to conduct an initial assessment of the effectiveness of soft tissue models when evaluating fit of protective clothing and equipment. The first phase of the project conducted a preliminary analysis comparing fit predictions while using traditional “hard” avatars with the advanced VitalBody “soft” avatars. That study was conducted using two synthetic body shapes (average male and average female shapes of CAF personnel) provided by DRDC, standing in a neutral pose. In the current phase, the focus of the study was to conduct more detailed, female-specific analysis, based on 3D scans of an individual, in operational poses.

Background

The background for the project was described in the statement of work and is included here to make this report more self-contained.

Proper fit and sizing of clothing and equipment is of importance to the Canadian Armed Forces (CAF). Fit is the result of a good match between an individual’s body shape and that of the garment’s intended user population. Improper fit is associated with skin irritation or soft tissue injury, reduced task performance, and compromised protection from external threats. For example, ill-fitted body armour may expose critical body regions to fragmentation or ballistic projectiles.

Fit is typically assessed utilizing clothing and equipment trials, using participants representing a range of body sizes and shapes. Performance-based and subjective data are collected and analysed to assess the suitability of the design or garment pattern, and to predict the portion of the population that will be accommodated by the design and size roll.

As human trials are costly and time intensive, virtual fitting is a new technique where digital patterns are fitted to human avatars. Information such as clothing drape, ease (air-gap between body and garment) and tissue pressure is then calculated. One limitation with virtual fitting is that the avatars are typically rigid shells that don’t account for tissue compressibility. While this is not an issue with lightly draped garments, it becomes a concern with close fit garments or rigid items such as ballistic plates which displace body soft tissue.

As there is increased interest in the requirement for body armour to conform to different body shapes (e.g., male and female forms), recent developments in soft tissue simulation [1, 2, 3, 4] have the potential to provide greater fidelity in quantifying the fit and coverage of body armour, comprising ballistic plates or hard armour, and fragmentation protection vests (FPV), or soft armour.

A preliminary assessment of the fit of Canadian hard and soft armour for representative average male and female Canadian Army torsos was conducted by Vital Mechanics [5] using a 2 x 2 x 2 study design. A comparison of the virtual static fit of Canadian body armour (elements most in contact with the body) was made, in two strap tightness conditions (loose and tight), for two CAF personnel models (average male and average female models, generated using PCA from 2012 CFAS 3D scans), using two types of avatars, either hard body avatars or avatars with soft body tissue models. Results identified local areas of high skin pressures at contact sites underlying the hard armour, particularly at the chest, though these were dramatically overpredicted when hard avatars were used in the fit assessment. Air gaps, important to avoid due to their contribution to thermal strain and reduced protective properties (both of which contribute to wearer vulnerability), were evident, again over-estimated when hard avatars were used for fit assessments. There were significant differences between male and female models; fit assessment using soft tissue modelling revealed significantly different pressures (at the chest) as well as air gaps (above chest) for the female model. These results support the contention that soft avatars are essential for fit prediction of tight fitting clothing such as body armour, and that anatomical differences between males and female need to be addressed when equipping CAF personnel.

Specific Aims of Phase 2

The specific objectives of this phase were to conduct more detailed analysis of the fit of protective equipment on the female body in different operational poses.

Approach

3D body scans of an individual female participant were provided by DRDC and utilized to construct more realistic soft avatars. The body armour tested was a Fragmentation Protective Vest (FPV) with inserted Bullet Resistant Plate (BRP), worn in two strap conditions ("comfortable" and "tight"). Pattern files and a physical sample of the FPV+BRP were provided to the contractor to guide garment modeling.

This project report is organized to mirror the four milestones of the project:

1. Development of rigid and soft body avatars based on sample CAF member geometry (Task 5.1);
2. Development of 3D finite element models of CAF FPV and ballistic plates (Task 5.2);
3. Virtual posing of avatar in each of a range of occupational positions or postures (Task 5.3);
4. Assessment of virtual fit of FPV on soft body avatars in each occupational posture (Task 5.4).

Results

Results are presented by task milestone in the following sections of this report.

Milestone 1. Development of rigid and soft body avatars based on sample CAF member geometry

We constructed 3D finite element models of the CAF participant based on 3D body scans taken on February 12, 2021 and supplied to us by DRDC. To obtain more accurate estimates of the body shape without external loads, the participant was scanned standing in a standard pose wearing two different bras with different levels of support, as shown in Fig. 1. One was a proprietary bra from Vital Mechanics designed to provide minimal support. The other was a standard supportive bra of the type typically worn with body armour.

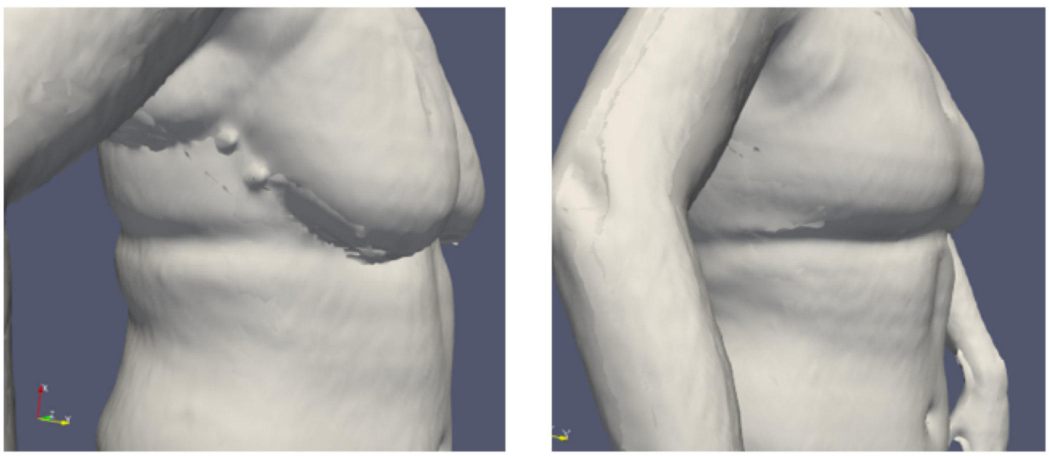

Figure 1: Scans wearing two different bras, which provided different levels of support: with a custom scanning bra supplied by Vital Mechanics, with minimal support (left); wearing a compressive sports bra that was later worn with the FPV (right).

A significant challenge with the scans provided was the presence of gaps in the occluded regions (such as armpits) and geometric noise in concave areas (see Figure 2).

Figure 2: Most 3D scanners, including the one used by DRDC, have difficulty scanning concave regions and occluded areas. These lead to holes and spurious geometry.

A second challenge, useful for future processing, was to remove markers and visible artifacts of a particular bra to make the soft avatars more generally useful. These challenges were overcome by a combination of manual clean up and template fitting. An “inner body” was then fitted to the surface mesh, representing the skeleton and deep fascia. A 3D FEM model of the soft tissue layer with spatially varying thickness and material properties was then constructed (see Figure 3). Unlike our previous work, the reconstruction was extended to the legs and arms since they may be in contact with the FPV in operational postures.

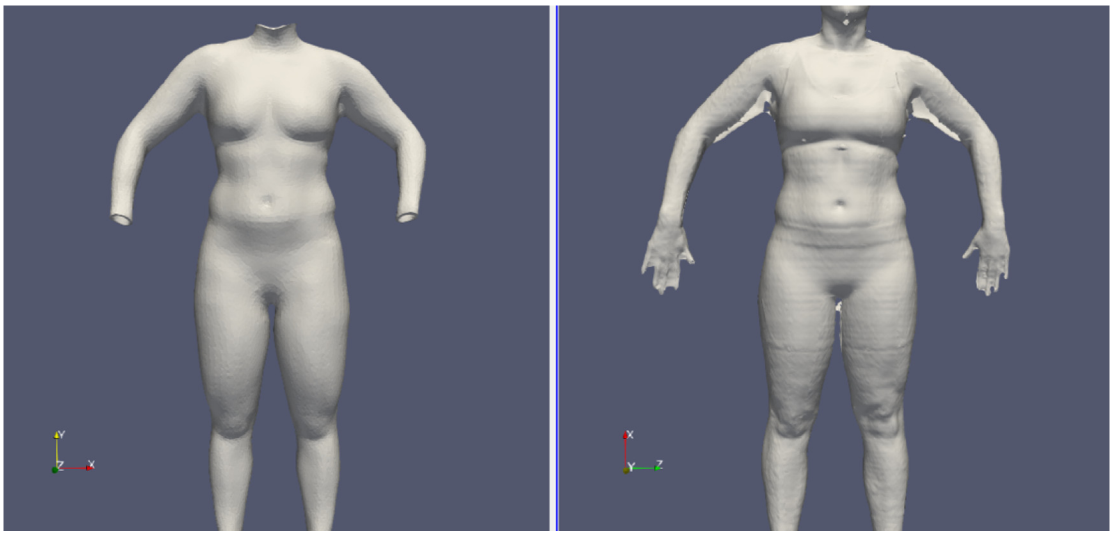

Figure 3: The 3D soft avatar constructed in standing pose, with FEM mesh (left). A scan of the participant in a similar pose is shown for comparison (right). Note that the extremeties are not fitted since they are not required for this work.

A close up of the FEM model for the two different bra conditions is shown in Figure 4. The FEM models capture the different levels of support of the two different conditions, and have filled in the gaps and removed artifacts of the worn bra.

The soft avatars were tested to ensure that the soft body avatars are capable of responding to contact, supporting two-way interaction with the FPV’s FEM model developed in Task 5.2

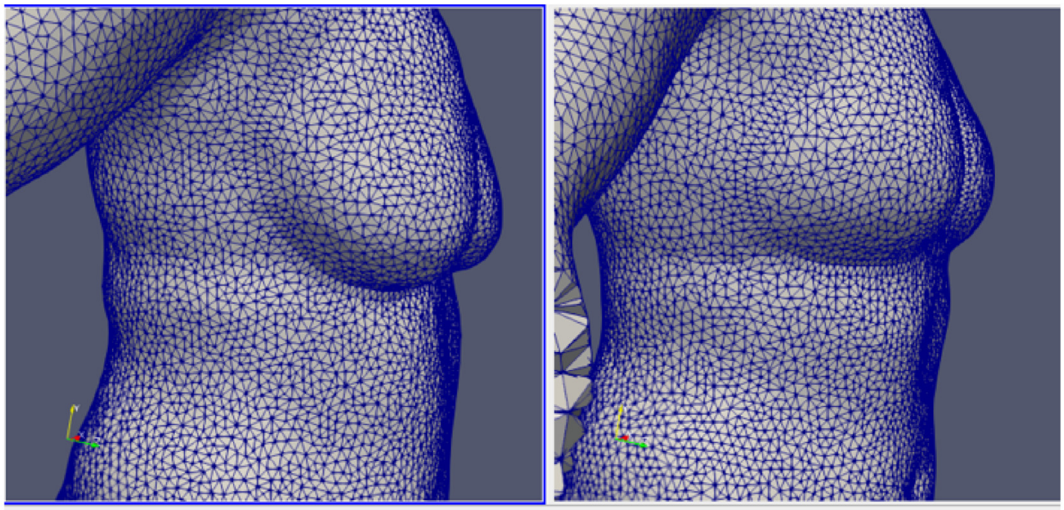

Figure 4: Finite element mesh of soft tissues of the body, in two different bra conditions.

Milestone 2. Development of 3D finite element models of CAF FPV and ballistic plates

We constructed 2D digitized pattern pieces of the FPV, informed by the physical FPV on loan to us, and the FPV pattern files provided to us. The pattern and sample were of the size expected to be later worn by the participant (size Med/Reg). The pattern files included a multitude of pieces from which the critical pieces for modeling fit were selected as for the previous analysis. These included the front and back panels with the locations of the pockets into which the BRP is placed (Figure 5). In addition, since it is relevant for posed avatars, we included shoulder pads and shoulder pad straps. The BRP was modeled as a curved shell that was fitted to match the dimensions of a 3D scan of the BRP. See Figure 6. Note that a shell, by definition, is represented by a surface (usually the medial surface) and captures the effect of thickness by incorporting a bending stiffness term. However, we also need a contact surface to model interaction between the BRP and underlying objects. We have chosen to represent the BRP using its inner surface; *this should be kept in mind when interpreting the depictions of the plates in images of simulations shown below*.

All pattern pieces and the BRP shell were discretized into FEM meshes, and sewn together to simulate the effect of the panels assembled in two strap tightness conditions (“comfortable” and “tight”).

To estimate the positions of the straps worn by the participant, we measured the position and girth of the FPV in the two tightness conditions from the 3D body scans, and estimated the amount of overlap in the panels. The assembled garment was placed on the body of each avatar, and a few initial simulations were conducted to ensure that the FPV+BRP model is ready for the next task. See Figure 7.

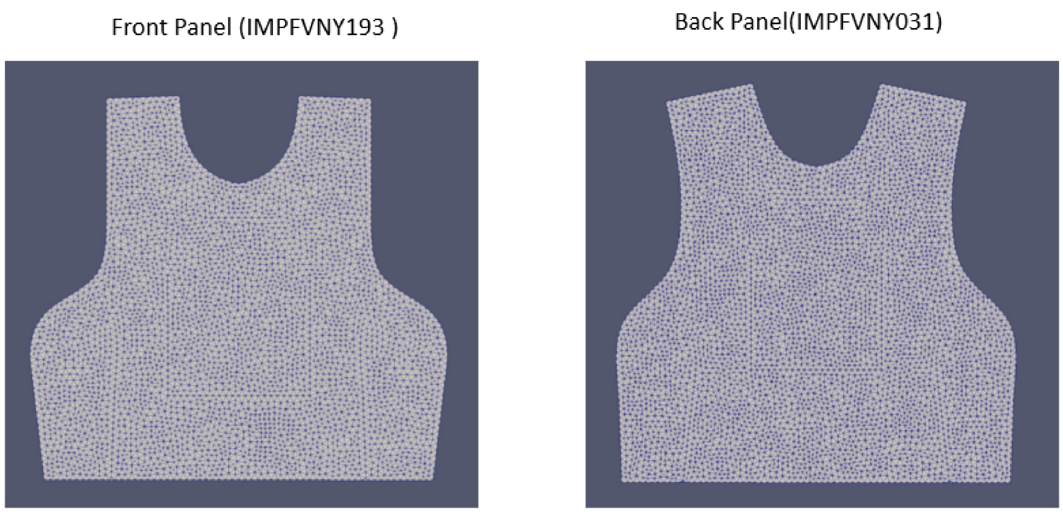

Figure 5: Finite element meshes of the front and back panels of FPV

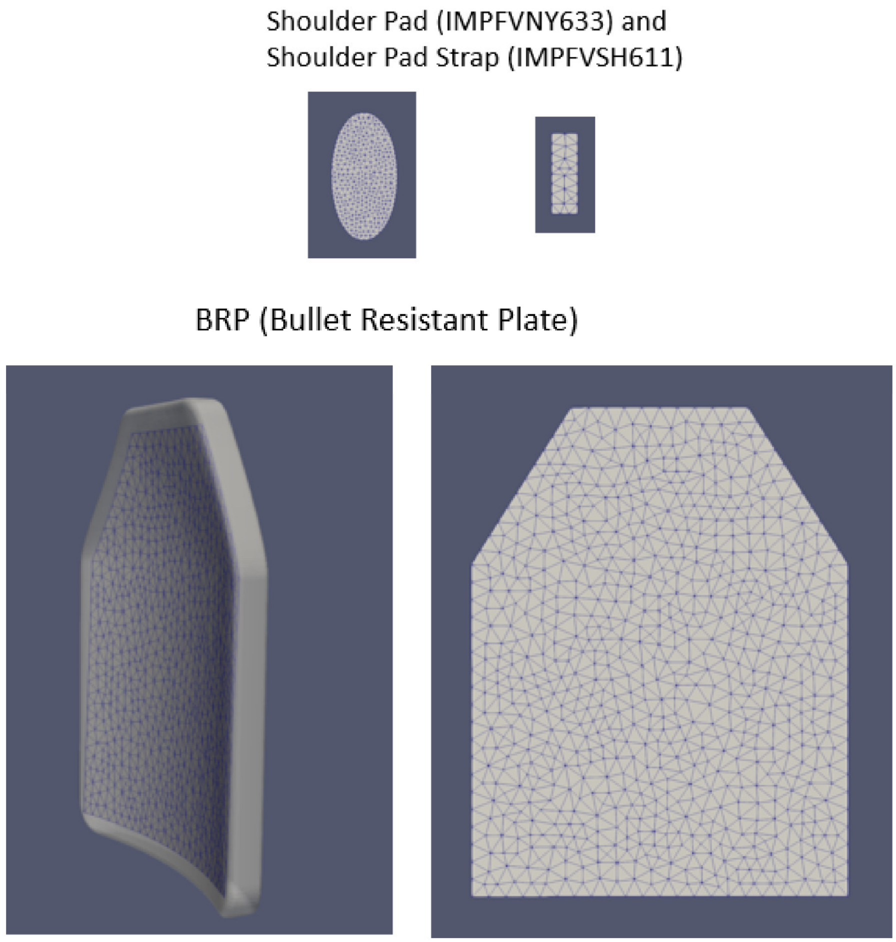

Figure 6: Finite element models of other key components of FPV+BRP that are in contact with the body in operational poses. These include the shoulder pad, with three short straps that attach the pads to the FPV (top), and the BRP (bottom).

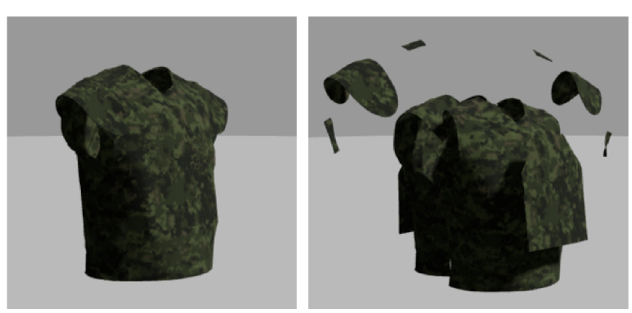

Figure 7: The assembled FPV, size Med/Reg (left). Note that only the BRP's inner surface is shown. An exploded view shows the different components (right).

Milestone 3. Virtual posing of avatar in each of a range of occupational positions or postures

We constructed posed avatars to match the postures in the scans provided by DRDC, in three static occupational postures: standing with arms to the side (which we shall henceforth call the "standing" pose), holding the arms as in firing a rifle, while standing (the "shooting" pose), and, without a rifle, seated, as if in the back of a troop carrier (the "passenger" pose). We initially planned to construct an avatar in the pose of firing a rifle while kneeling, but scans in that posture had severe occlusions, both from the other parts of the body in a kneeling pose and from the rifle. In consultation with the Technical Authority, we replaced the kneeling pose with that of standing while holding the arms in a shooting pose. Even in this pose, there is significant occlusion leading to holes in large parts of the torso (see image on the right of Figures 8 and 9).

In each of the occupational postures we identified body landmarks on the scans of the CAF participant in that pose. We then estimated the skeletal pose of the avatar in each of the occupational postures. The skeleton, as well as the inner surface of the soft tissue layer, was then transformed to the occupational posture. Soft tissue simulations were performed to estimate the initial configuration of the avatar surface in the occupational posture.

Figures 8 and 9 show the results of constructing the posed avatar for the shooting pose, and Figure 10 shows the seated soft avatar in the passenger pose.

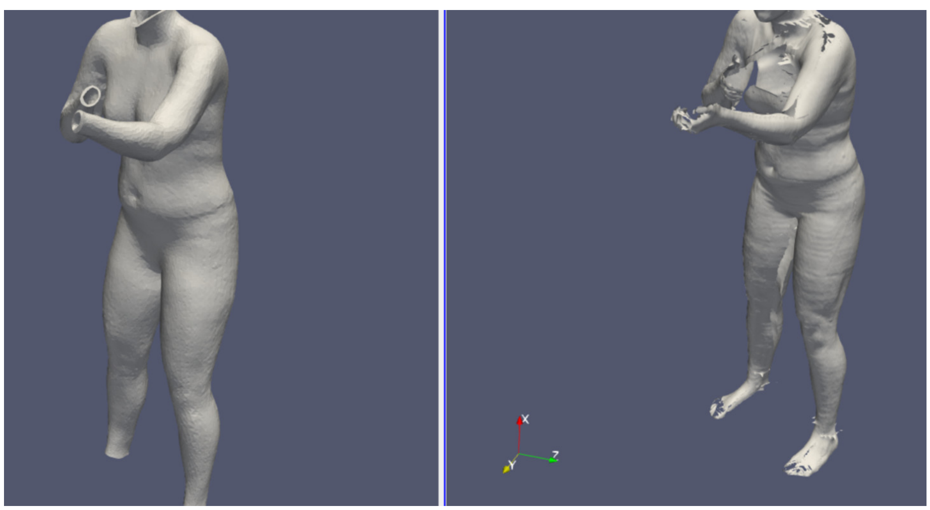

Figure 8: Posed avatar in the shooting pose (left), posed to match the scan (right). Observe that the scan is missing large parts of the torso which are occluded by the arms, and there are several other holes. Our posed avatar fills the gaps in the data, and constructs a 3D FEM model of the soft tissues of the body.

The FPV, in each of two tightness conditions, was positioned on the body in the occupational postures as follows. We first positioned it on the body in the standing pose, and quasi-statically simulated the change of pose of the body from standing to the occupational pose. The FPV moved with the body due to contact and our simulation. This provides the initial placement of

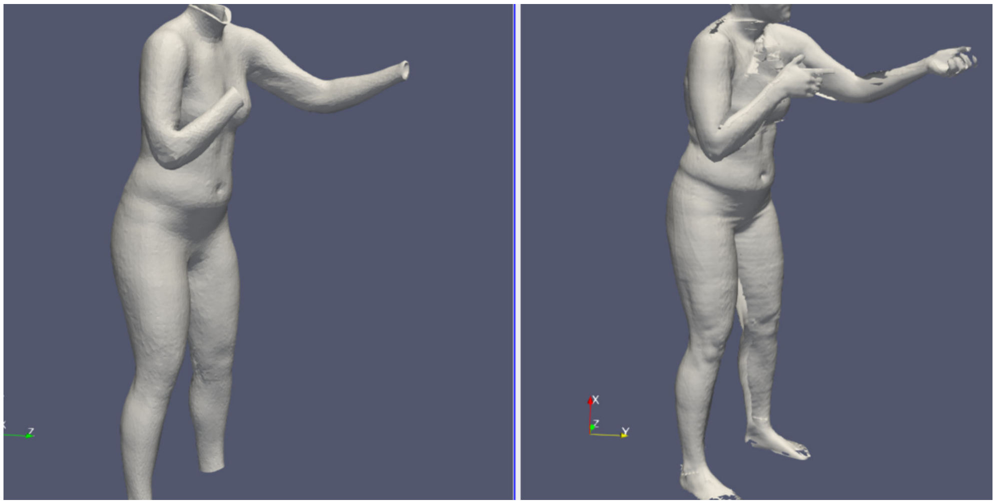

Figure 9: Another view of the avatar (left) and scan (right) in shooting pose.

the FPV, in each of the 2 FPV tightness conditions, for each occupational posture. The initial placement was thus ready for the next Task of finite element analysis of FPV fit. The resulting posed avatars are shown in the next section.

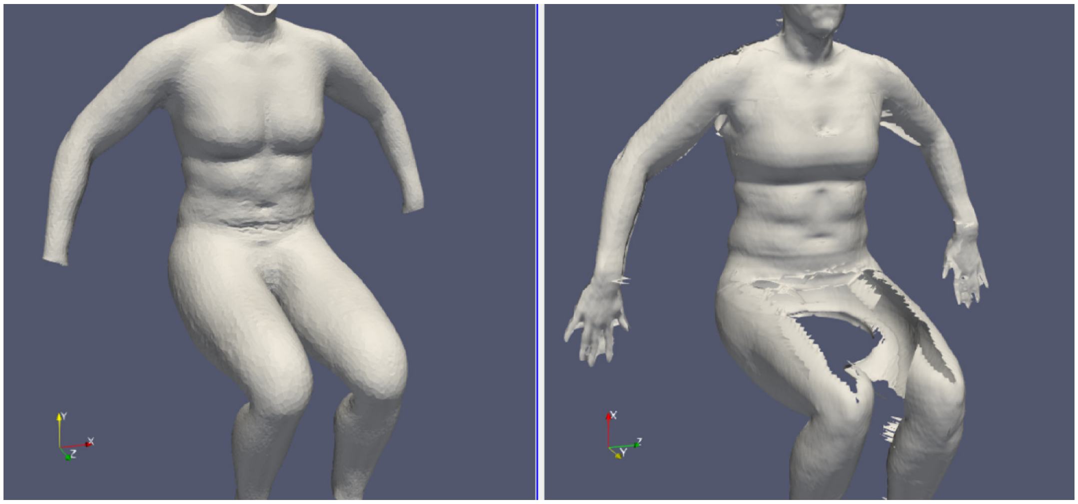

Figure 10: Posed avatar (left) and scan (right) in passenger pose. Observe that large parts of the legs and inner arm areas are missing in the scan. Our method is able to fill these gaps in the data.

Milestone 4. Assessment of virtual fit of FPV on soft body avatars in each occupational posture

We conducted FEM studies to assess the fit of the armour in each of 3 postures in two FPV tightness conditions ("comfortable" and "tight"). These simulations were conducted with the avatar corresponding to the standard bra only, since that was the only bra worn by the participant in scans with the FPV.

In performing this task, we discovered that the length of the FPV that we had modeled, based on pattern files and the physical garment (Med/Reg) supplied to us, was about 3cm longer than what was observed in the scans of the CAF participant. The Technical Authority subsequently confirmed that the participant had indeed worn a shorter FPV (Med/Short). Since the pattern files for the correct size were not available to us, we accounted for this discrepancy by measuring the approximate length of the front of the FPV from a 3D scan and reducing the length of the FEM mesh to match the scan. See Figure 11. While this addressed the length discrepancy, it not known whether there are other differences in construction and proportions of the actual garment worn by the study participant.

Figure 12 shows the FPV in a tight strap condition, worn in a standing pose. The FEM simulation lacks many of the visual details due to side straps, velcro pads, and other components that were not directly represented in the simulation. But the overall placement of the FPV on the body appears to be similar. Note that it is not possible to directly superimpose the scan and the simulation, since the simulation is based on the participant scanned without wearing the FPV, and there are small but significant postural changes between two scans of the same person. Also, please keep in mind that the FEM mesh shown represents the *inner surface* of the thick fabric panels and BRP, and therefore may appear narrower than the scan.

Figure 13 shows how the body is compressed by the FPV, especially by the BRP pressing

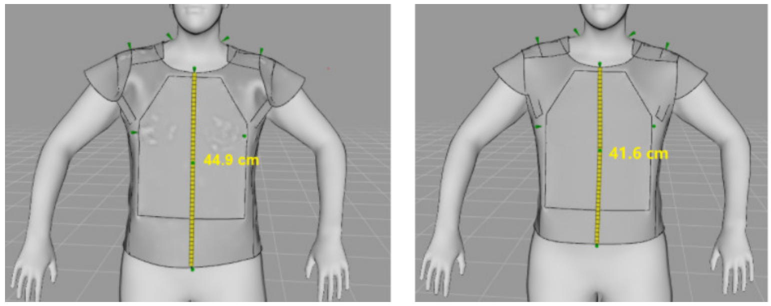

Figure 11: The FPV and pattern files supplied to us were of size Med/Reg, which we initially used to construct the FPV (left). The lower margin of the FPV was shortened to match the length of the Med/Short size as measured from the 3D scan.

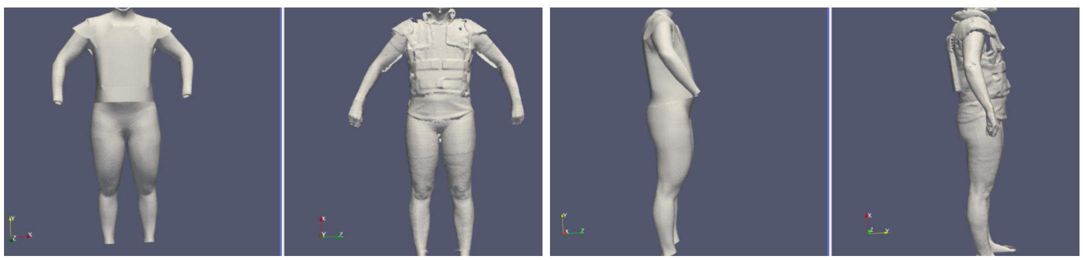

Figure 12: Placement of FPV, in the tight strap condition, on avatar vs. body scan.

against the chest. Figure 14 provides another visualization of soft tissue compression, and compares the effect of strap tightness.

Soft tissue compression of the female avatar was further investigated by quantifying the air gap and contact pressure between the armour and body. Since the differences between rigid and soft tissue avatars are very large and obvious, and also reported in the previous study, we focus on the smaller differences between the two strap conditions (**comfortable** and **tight**). We report peak values in three regions of the body, termed: (1) **shoulder**; (2) **chest** (including the region at the height of the breast and the top margins of the BRPs); and (3) **hip** (ranging from abdomen to hip, including the areas covered by the lower margins of the BRPs).

Figures 15 and 16 show the estimated air gap between the body and the FPV. Consistent with our previous study, the air gap is lower for soft avatars relative to hard avatars due to soft tissue compression, and is lower for the tight strap condition compared to the comfortable strap condition. However, there were significant regional differences. The peak air gap in the chest occurred at the top of the BRPs and was essentially unchanged between the two strap conditions in the front (2.1 cm) but decreased from 2.6 cm to 2.2 cm in the back. By contrast, the peak air gap in the hip region occurred at the bottom of the front BRP and decreased significantly from 4.4 cm to 3.6 cm. These results are consistent with displacement analysis in Figure 14.

Figure 17 shows the pressure on the body under the FPV in the two strap conditions. Even though the inward displacement of the breast did not increase significantly, the peak pressure increased from 11 to 13 mmHg, and the pressure on the abdomen also increased from 1.4 to 1.7 mmHg. Somewhat unexpectedly, in the standing pose the peak pressures were on the shoulder

Figure 13: Body shape in the semi-nude condition, before wearing FPV (left), which is also the shape of a rigid avatar. There is significant soft tissue deformation due to the FPV, especially in the breast area, as shown for the FPV in the tight strap condition (right).

and not on the breast, even in the tight condition. Figure 18 shows the pressure with tight straps in two views that permit a clearer view of the shoulder; the peak pressures were 24 mmHg in the comfortable strap condition and 23 mmHg in the tight condition. There was also significant bilateral asymmetry, presumably due to the asymmetry of the body in the pose of the participant in the scan: the local peak pressure was 23 mmHg on her right shoulder and 17 mmHg on her left shoulder in the tight condition.

The higher pressure observed on the shoulder could be realistic, due to the weight of the armour and, in part, due to the low friction values (friction coefficient of 0.2) between the body and FPV used in the simulations. This may place most of the burden of load carriage on the shoulders. Interestingly, the peak pressure was slightly *lower*, by about 5%, in the tight strap condition compared to the comfortable strap condition, suggesting that tighter straps distribute the load to other parts of the body, reducing the load on the shoulder; such a load re-distribution effect could be higher with increasing friction between body and armour.

To summarize the results in the standing pose, we observed large differences between predictions of the fit of the FPV when using rigid avatars compared to soft avatars (Figures 13 and 14), particularly in the breasts of the female participant. Interestingly, increasing the strap tightness did not increase the inward displacement of soft tissues of the breast, presumably because they had already compressed to close to their maximum range, which is limited by the rib cage (Figure 14); consistent with this observation, the maximum air gap in the chest segment did not

Figure 14: The body shape before wearing the FPV (white) is superimposed on the body shape compressed by the FPV (blue). Therefore, visible white areas highlight those that were pushed in by the armour. The left image shows the “comfortable” strap condition and the right image shows the “tight” strap condition. The greatest differences, highlighted in red, appear to be in the lower abdomen and sides, with additional inward displacement of soft tissue in the tight condition.

increase (Figures 15 and 16). However, the pressure on the chest and hips increased by about 20%. Peak pressures occurred on the shoulder, slightly exceeding 20 mmHg, and decreased with increasing strap tightness. Shoulder pressure could be decreased further by increasing friction between body and armour to redistribute the load. This suggests that characterizing friction (which was not done in this study) is important for predicting load distribution and requires further study.

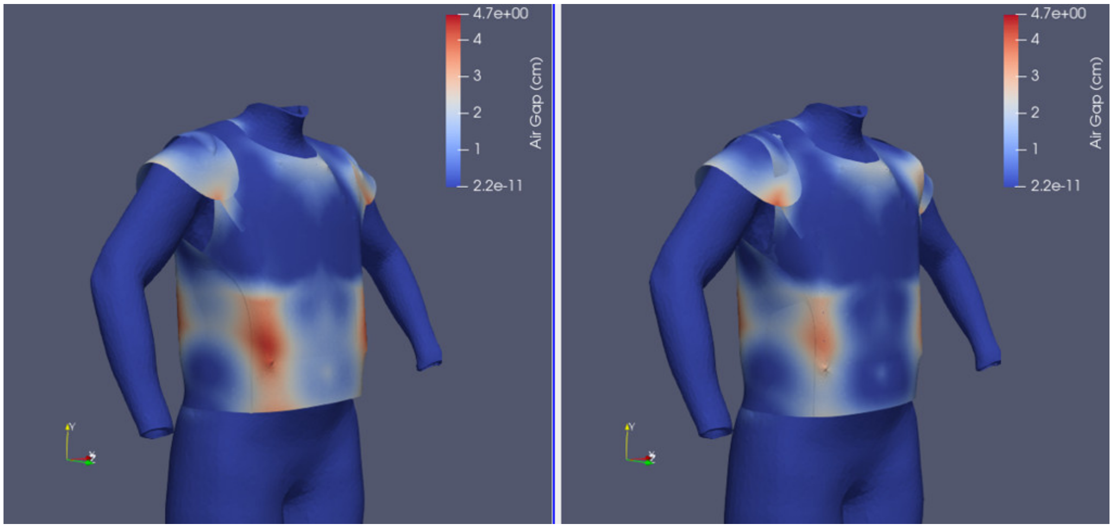

Figure 15: Comparison of air gap for the comfortable strap condition (left) and tight strap condition (right).

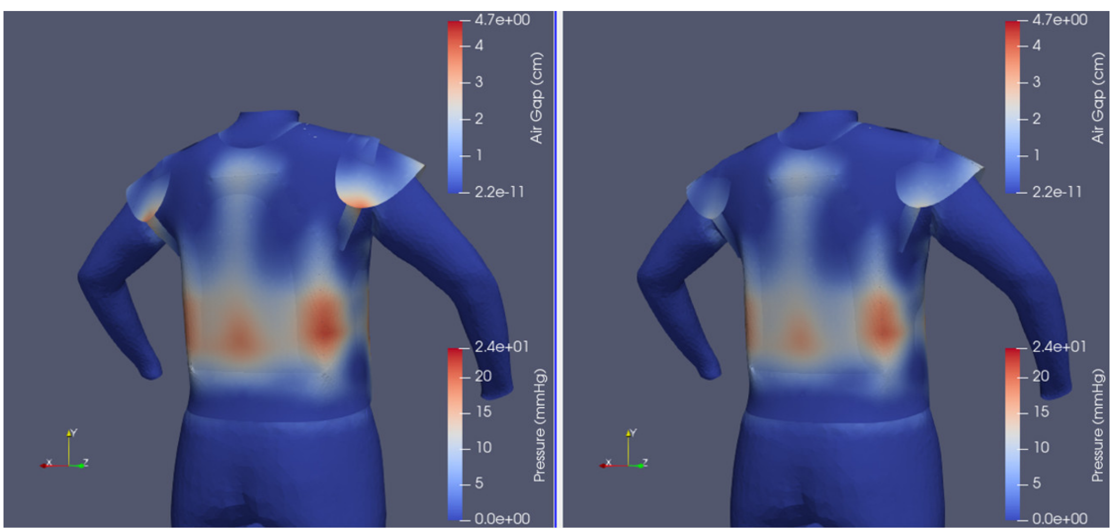

Figure 16: Another view of air gap for the comfortable strap condition (left) and tight strap condition (right).

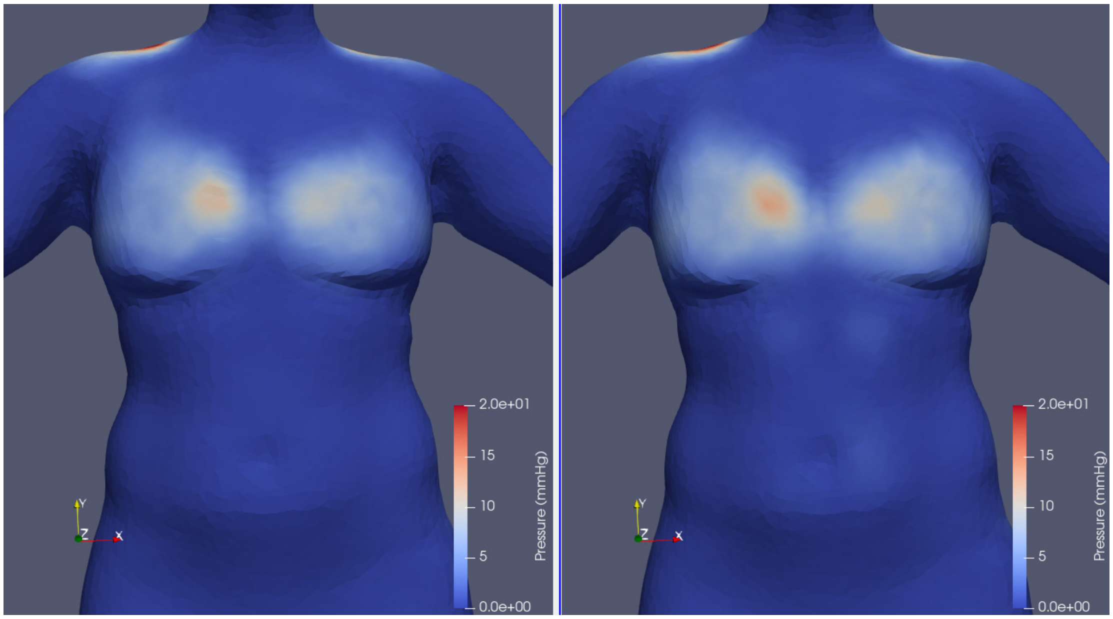

Figure 17: Pressure on the body in mmHg under the FPV worn in the comfortable (left) and tight (right) conditions.

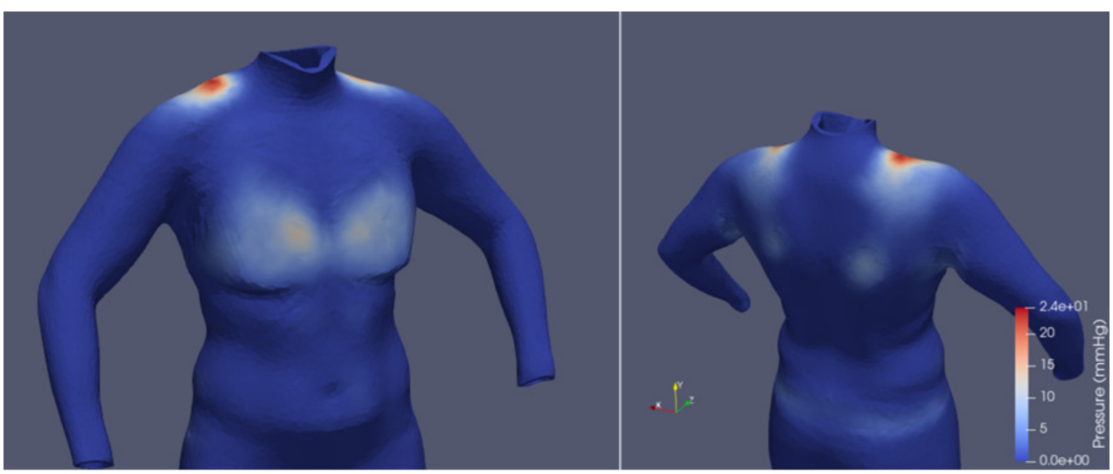

Figure 18: Pressure on the body in mmHg under the FPV worn in the tight condition, shown in two views.

Next, we analyze the fit of the FPV in two operational postures. Figure 19 shows the FPV worn in the seated condition.

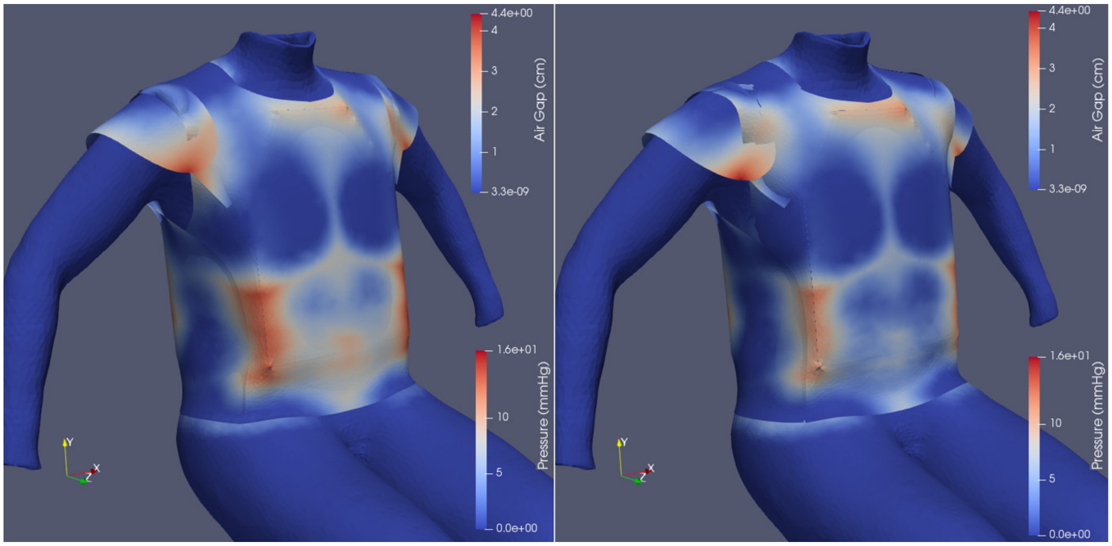

Figure 19: Air Gap between body and FPV in the comfortable (left) and tight (right) strap conditions.

The soft tissues of the abdomen appear to contact the BRP over a larger region, and there is additional contact and support at the lower margins of the FPV. The air gap decreased at the sides and the lower margin of the FPV, but the peak air gap increased at the margins of the BRPs. Interestingly, tightening the strap *increased* the peak air gap at the chest (top margin of the BRP), from 2.9 cm in the comfortable condition to 3.2 cm in the tight condition. The effect was the opposite in the hip region. Tightening the strap decreased the peak air gap at the bottom-side margins of the BRP, from 4.1 cm in the comfortable condition to 3.6 cm in the tight condition. This phenomenon could be due to the BRP being pushed up in this posture. Another possibility is that the side straps that were tightened were below the level of the breasts; the rigid BRP may pivot on the breasts, like a seesaw, decreasing air gap below the breasts but increasing it above. These effects may need to be considered in designing straps for female body armour.

The distribution of pressure between the shoulder and chest changed in the seated posture, with greater pressure on the chest and hip regions, and less pressure on the shoulder. This can be seen in Figures 20 and 21. In the chest region, pressure on the breasts increased to 14 mmHg (compared to 13 mmHg standing) in the comfortable condition, and increased further to 16 mmHg in the tight condition. A significant effect is the increase in pressure on the hip area and lower back in this posture, which increased to 3.6 mmHg (compared to 1.8 mmHg standing) in the comfortable condition, and increased further to 5.6 mmHg in the tight condition. The corresponding pressures on the back of the hip were 2.9 mmHg in the comfortable condition, increasing significantly to 9.3 mmHg in the tight condition. The increased hip pressure is due to contact with the edge of the FPV, and is likely to be greater for females than for males due to differences in body shape. Note that we approximated the size of the Med/Short FPV; in real life

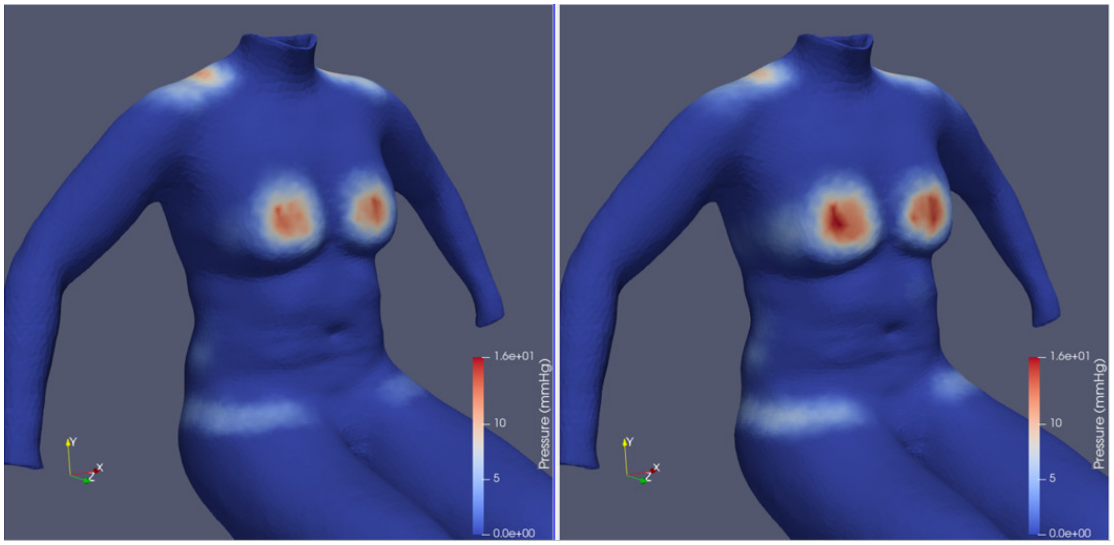

Figure 20: Pressure on the body measured in mmHg, in the comfortable (left) and tight (right) strap conditions.

this FPV may be shorter or the soldier may adjust the placement of the FPV upwards to make it more comfortable in the sitting posture. Also, please note that these changes were solely due to the postural change, and not due to contact with a seat back. Future studies could examine the effect of leaning on a seat back (or lying on the ground) with the rigid BRPs in contact with the external environment.

Next, we analyzed the changes in the fit of the FPV in the shooting pose. Please note that this condition was challenging due to the complexity of modeling articulations of the shoulder pad and attachments when the arm is raised. For this study the pads were attached by sewing. Modeling shoulder pad behavior accurately requires more effort before we can be confident of the simulations in this posture, but we can make some preliminary observations. Many of the features of the fit were similar to standing, but there were differences due to the fact that the left arm was raised to support the weapon. The air gap increased to 3.2 cm at the top of the left BRP, closest to the raised arm. Figure 22 shows the pressures on the avatar in the shooting pose. The biggest change is the increase in pressure on the armscye between the shoulder and upper arm, due to contact with the shoulder pad and main panels of the FPV (10 mmHg in comfortable condition, and 12 mmHg in the tight condition). Note that the peak pressure on the shoulder also decreased relative to standing because the load is now distributed over a larger region. There was minimal pressure on the abdomen in this posture, but the pressure on the shoulder blades of the back increased (to 11 mmHg in the comfortable condition and 8 mmHg in the tight condition), presumably due to a slight forward tilt of the back. The increased pressure on the arm may lead to a reduction in range of motion of the arms due to pressure and discomfort from contact with the FPV.

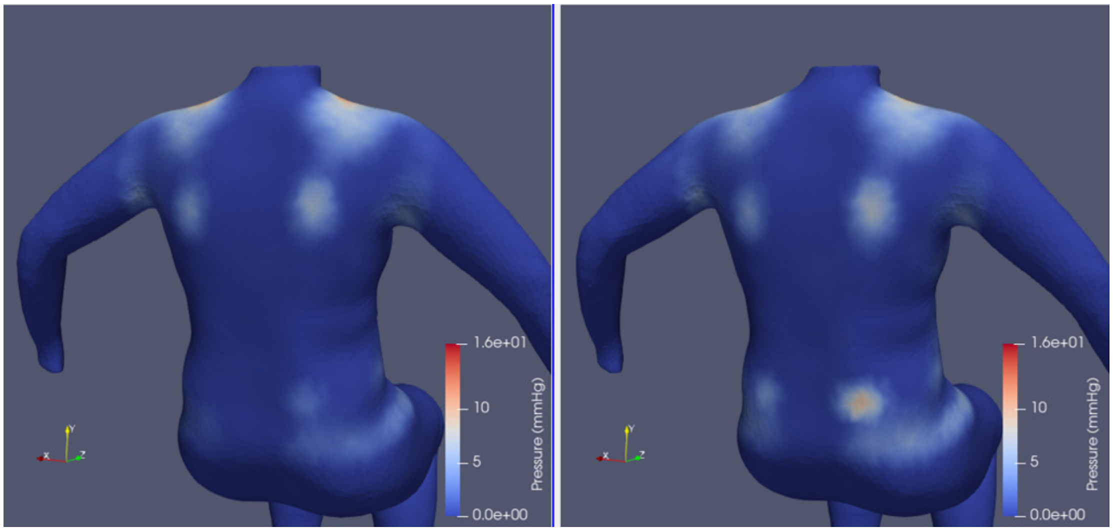

Figure 21: Back view, showing pressure on the body measured in mmHg, in the comfortable (left) and tight (right) strap conditions.

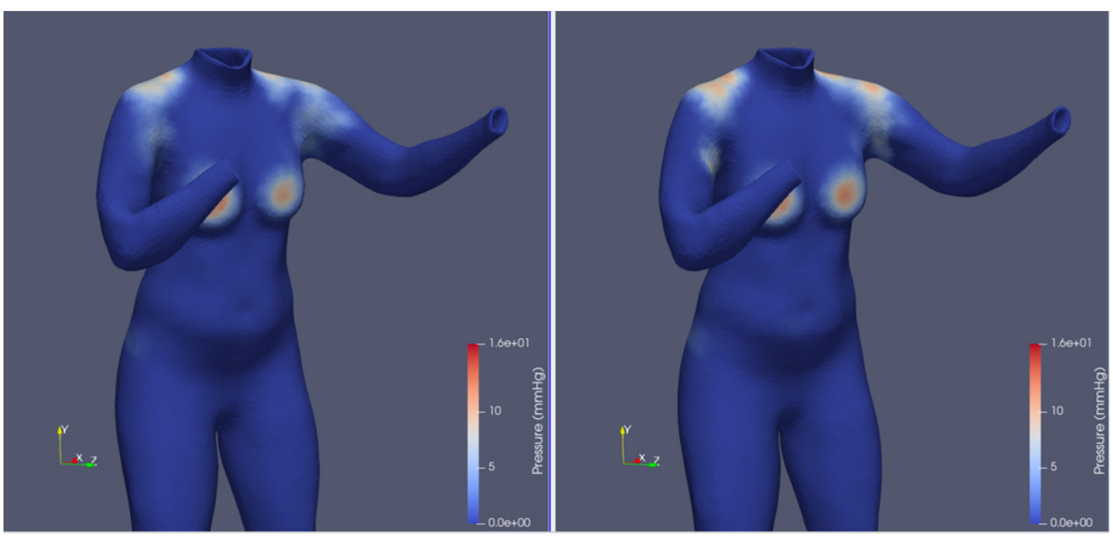

Figure 22: Shooting pose showing pressure on the body, measured in mmHg, in the comfortable (left) and tight (right) strap conditions.

Conclusions and Recommendations

The major advances in this study were to take the important step from our previous analyses with synthetic body models in single standing pose, to scans from a real human participant in multiple poses. The study also addressed specific aspects of body armour when worn by female personnel. Even though this was a small study, we successfully addressed several challenges. Perhaps the greatest challenge, overcome by the DRDC team, was to obtain scan data while coping with the constraints of the COVID-19 pandemic.

The new results confirmed the results of our previous study that there are significant differences in predictions of the fit of female body armour using soft avatars, compared to traditional rigid avatars. These effects were significant for the female participant, and were observed not only on the chest but also on other areas such as the hips.

The soft tissue deformation of the breast region was highly non-linear and showed some surprising consequences for changes in air gap and pressure with changes in strap tightness. The breast region, primarily comprising adipose tissue, deforms quickly at low pressures but the maximum inward displacement in limited due to the underlying rib cage and volume preservation of the soft tissues. Increasing tightness of the side straps did not increase the inward displacement at the breast significantly. In the seated posture, the BRP moved like a seesaw pivoting on the breast, decreasing the airgap at its lower margin while increasing the air gap at the upper margin. Such results may be used to evaluate the protection and thermal comfort of female body armour.

Peak pressures were observed on the shoulder and not on the breast, even on the female body, in our simulations. Increasing strap tightness decreased the pressure on the shoulder and increased it on the breast, suggesting that peak pressures could be reduced by choosing appropriate values of strap tightness. However, increasing strap pressure has other consequences; increased pressure on the chest which may make breathing more difficult and lead to breast discomfort. Increasing friction between body and armour could also increase the redistribution of load away from the shoulders. Friction was not measured in this study, it could be manipulated by choice of garment worn between the armour and the body. However, increased friction could have other consequences, such as increased chafing. Future studies could investigate these effects.

Another interesting finding is the change in pressure and air gap due to postural changes. The location of high-pressure areas on the body varied with posture, with larger pressures observed on the hip and lower back during sitting and in the armscye areas during shooting. These pressures could lead to discomfort, distraction, and could limit the range of motion. Since the BRP's weight is partly supported by the hips and thighs in the seated posture, the pressure and discomfort may depend on the size of the BRP relative to the size of the torso and the width of the hips, and may affect average female bodies more than average male bodies. These questions, as well as pressures due to contact with a seat back, merit further study.

For the FPV modeling, we opted to include the shoulder pads along with their retaining straps, since we suspected that they would be important for the change of posture. The pads proved to be challenging to model. The pads, along with the retaining straps, form an articulated mechanism that slides over the shoulder and the other parts of the FPV. Our results show that in the shooting posture, contact with the shoulder pads contributes to increase in pressure and potentially to a decrease in range of motion. Another contributor to pressure was contact with the edges of armscye that is formed as a gap between the two main panels of the FPV. The results suggest that proper sizing, as well adjustment and placement of the two panels affect the opening of the armscye; that, in turn, is an important factor in comfort and range of motion.

On the technical front, the present study identified and overcame several challenges in dealing with scans of human participants in operational poses. **Robustness to scan quality:** Unlike the previous study, which used water-tight synthetic avatars in a standard "A" pose, this study started from raw scans. The scans had missing data and spurious geometry in parts of the body that were occluded by other parts of the body in operational postures. Such problems are found in even the best scanners. Vital Mechanics' body fitting technology was able to address these challenges. **Posable soft avatars:** A second challenge was to construct a consistent soft tissue FEM model for the three poses. Note that this is not just a problem of posing the outer "skin" of the avatar as is done in games and movie visual effects. For soft tissue simulation we also needed to estimate the shape of the "inner body" of the skeleton and other deep tissues in the different poses in a consistent manner. We successfully posed and registered the FEM models in three postures: standing, sitting as in the back of a troop carrier, and holding the arms up in a shooting pose. Our solution is quite general, and could be used in future to fit other poses.

The present study had a few limitations due to the late availability of scan data, and COVID-19 restrictions on the amount of scanning possible. The participant was scanned wearing the FPV in only one bra condition, and therefore we conducted FEM simulations only for that condition. The shoulder pad's contact with other parts of the FPV was modeled by placing small stitches between a pad and main panels underneath. A fully articulating pad would be preferable. Finally, and most importantly, this was a single study with one participant; to draw reliable conclusions the study should be repeated with a larger number of participants with different body types.

The study provided some unexpected support for the utility of virtual fit testing with VitalFit. We noticed, during our simulations for Milestone 4, that the FPV wasn't fitting the avatar well at the front of the thighs while sitting down. After discussion with the Technical Authority we learned that the size we had been issued was not the one actually worn by the participant! This required some additional time and work to construct a new FPV model. Nevertheless, these results showed, in a small way, the ability to detect poor fit using VitalFit virtual fit testing! It presages an effective procedure to compute the best size of body armour for a soldier from their scan data.

Several avenues for further research and exploitation are available for the near future, some of which were already listed in the previous report. In the following we updated those recommendations with new data and priorities.

Potential Next Steps – R & D

The assessments so far point to several potential refinements and analyses that could advance the knowledge and techniques available to improve the fit and function of protective clothing, and for exploiting 3D body scanning technology for that purpose.

1. Additional Analyses and Simulations.

(a) Additional operational poses. The DRDC team has already collected additional 3D scans of the female participant in other important operational postures, including driving, kneeling while firing a rifle, stepping up. Simulating and analyzing these postures was not within the scope of the current Task Authorization. The scans are also more challenging to analyze due to greater occlusion. A natural next step is to model and analyze this useful data set that already been collected by DRDC to understand the impact of body armour on a female soldier during combat operations.

(b) Load carriage by female soldiers. Strap pressures account for a lion's share of the discomfort during load carriage, and recent work has suggested that shoulder straps are much more important than hip straps, but these studies exclusively used young male subjects. Hip belts and harnesses can compress the lateral femoral cutaneous nerve, leading to meralgia paresthetica; an interesting observation is that in the US military, servicewomen have higher rates of this condition than servicemen, and rates increase with age. This suggests that these hip belts may not have considered the differences between female and male hips, and changes with age. Redistribution of load due to different levels of strap tightness and friction also needs to be considered. It may be useful to compute the load-dependent pressure distribution over the body, for different body shapes, especially in the hip region.

(c) Accessibility/visibility computations. The results showed that air gap and pressure estimates with soft avatars can be very different from estimates using hard avatars. Additional simulations and analyses could be performed evaluate accessibility/visibility to support vulnerability/lethality modeling, using soft avatars to predict the coupling between soldier and equipment.

(d) Modeling details. The model used in this study approximated the contact between the shoulder pads and the FPV by stitching it at a few points to represent contact. This was done primarily for computational efficiency to focus on contact between the body and the FPV, and to avoid additional contact processing between different components of the FPV. Additional studies could construct more detailed models with full contact processing between layers of the FPV, including fully articulating shoulder pads.

2. Mobility and range of motion for occupational movements. In the current study we evaluated fit in specific occupational postures, but we did not evaluate whether the soldier can comfortably move from one posture to another. We also did not evaluate mobility of the torso *within* the FPV, e.g., articulations of the spine for reaching and bending. Such a capability is essential to evaluate the range of motion in more detail than was possible in the present study. This would require animating the soft avatar with the body armour worn.

3. Breathing when wearing protective ensembles. A particularly important direction is to model changes in chest shape and volume during respiration, which may be important for predicting fit during vigorous activity. The studies so far suggest that the tight strap condition could be better for reducing the air gap under the FPV, but this could have a negative effect on mobility of the chest wall that is required for breathing.

4. Measuring soft tissue properties of CAF personnel. It has recently become possible to measure soft tissue properties quickly and easily using a hand-held probe. This technology was invented at UBC and Vital Mechanics has recently developed the next generation of that device, called the Vital Probe, with high resolution sensor for measuring tissue properties within seconds. Such measurements can lead to not only better soft avatars, but also for other applications such as estimating adiposity and BMI of individual personnel or recruits.

Potential Next Steps – Exploitation

Vital Mechanics's current capability, demonstrated in this project, could be exploited to support recruiting and equipping Canadian Forces. Canada is fortunate to have had a head-start in collecting anthropometric data and 3D body scans of armed forces. Thanks to the 2012 Canadian Forces Anthropometric Survey, Canada already has a database on 3D body scans collected on over 2200 CAF personnel.

Vital Mechanics can covert these 3D scans into VitalBody soft avatars that can be used to evaluate the fit of protective equipment, load carriage, uniforms, and headgear. Such a database of CAF VitalBodies may be used to improve operations and respond to new challenges.

Scanning all incoming military personnel is also technically feasible. Scanning equipment is likely to become inexpensive in the near future due to the growth in the consumer market for depth cameras (ranging from Intel's RealSense technology to depth cameras in smart phones). Vital Mechanics can convert data from these devices into VitalBody avatars. This enables the creation of a "digital twin" of each individual CAF person that could support multiple uses throughout their service, current and future. A potential collateral benefit is that the use of high technology by Canadian Forces is likely to be motivating for the younger generation of recruits.

Armed with a database of VitalBody soft avatars of CAF personnel, it is possible improve operations by answering difficult questions such as:

- What equipment to acquire? CAF can test inclusivity by sex, morphology, and body composition by virtually fitting equipment on avatars in the database. By batch running all user scans through the model, DND can rapidly learn the percent population accommodation of in-service, any proposed modifications to in-service, or any replacement items clothing and equipment (thus better demonstrate compliance with GBA+ policies).

- Where to prioritize to achieve optimal diverse population accommodation?

  One can baseline the population accommodation of in-service clothing and equipment in order to prioritize investments for item redesign or replacement.

  Conduct "what if" analyses on ideas/virtual solutions to overcome designs that exceed skin pressure tolerances, impede soldier movement/ROM, or that are the source of numerous subjective complaints about an item of issued clothing or equipment.

  Determine how many items to stock? Inventories and geographic distribution of equipment could be optimized based on the database.

- Which one should I use? The database may be used to personalize fit, so that each soldier has the best fitting equipment.

The database could help respond to new challenges, such as the COVID-19 pandemic. It could help optimize and tradeoff between safety, mobility, and comfort in new designs. A database of VitalBody avatars could help quickly design, test, and personalize new equipment with little downtime for active duty personnel.

In summary, the virtual fit testing technology demonstrated here will contribute to ensuring that Canadian Armed Forces can accommodate more diverse personnel of different genders, body shapes, BMIs. It has been widely reported that current body armour does not fit female soldiers well and may be a barrier to recruitment and retention of female soldiers. It has also been reported that smaller men and women also struggle with existing body armour. Our VitalFit software could contribute to Canada's goal of a military that is at least 25% female by 2026.

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Abbreviations and Acronyms

BMI	Body Mass Index
BRP	bullet resistant plate(s)
CAF	Canadian Armed Forces
CFAS	Canadian Forces Anthropometric Survey (2012)
DRDC	Defence Research and Development Canada
FEM	Finite element model(ling)
FPV	Fragmentation Protective Vest
PCA	Principal Components Analysis
R&D	Research and Development

DOCUMENT CONTROL DATA *Security markings for the title, authors, abstract and keywords must be entered when the document is sensitive	
1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.) Vital Mechanics Research Inc. 3522 W. 22nd Avenue Vancouver, (BC) Canada	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) CAN UNCLASSIFIED 2b. CONTROLLED GOODS NON-CONTROLLED GOODS DMC A

3. TITLE (The document title and sub-title as indicated on the title page.) Soft Body Simulation for the Fitting of Protective Equipment: Phase 2 Female-Specific Analysis
4. AUTHORS (Last name, followed by initials – ranks, titles, etc., not to be used) Pai, D.

5. DATE OF PUBLICATION (Month and year of publication of document.) March 2021	6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.) 29	6b. NO. OF REFS (Total references cited.) 5

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.) Contract Report
8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.) DRDC – Toronto Research Centre Defence Research and Development Canada 1133 Sheppard Avenue West Toronto, Ontario M3K 2C9 Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) Human Systems Performance (HSP)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) W7719-205487/TOR/001
10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC-RDDC-2022-C056	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.) Public release
11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

virtual soldier; digital human modelling; body armour; 3D modelling; female-inclusive armour; soft tissue; ballistic protection; thermal insulation

13. ABSTRACT/RÉSUMÉ (When available in the document, the French version of the abstract must be included here.)

Aims: The primary aim was to evaluate the use of soft tissue models to assess the fit of protective clothing and equipment on female CAF personnel. Additional aims were to construct the soft tissue models from raw 3D scans provided by DRDC, and to assess fit in operational postures.

Outcomes:

Effectiveness of soft avatars. The results demonstrated more realistic predictions of fit using VitalFit soft avatars compared to hard avatars. Soft tissue compression in the breast and hip regions produced significant differences in airgap and peak pressures. In an earlier part of this study, we also showed that these differences are greater for female bodies compared to male bodies.

Implications for female body armour: The study showed some surprising consequences for changes in air gap and peak pressure with changes in strap tightness and posture for female personnel. Strap tightness decreased airgap and also peak pressure, but not uniformly. Peak pressures were observed on the shoulder and not on the breast, even on the female body, in our simulations. The location of high-pressure areas on the body varied with posture, with larger pressures observed on the hip and lower back during sitting and in the armscye areas during shooting. These pressures could lead to discomfort, distraction, and could limit the range of motion. Such results may be used to evaluate protection, as well as physical and thermal comfort, of female body armour.

Demonstration of Technical Capabilities: (1) Robust construction of soft avatars from raw scans, even in the presence of significant scanning artifacts. (2) Posable soft avatars. We demonstrated the capability to pose and register the avatar, including the soft tissue FEM model, in three operational postures: standing, sitting as in the back of a troop carrier, and holding the arms up in a shooting pose. These results suggest that it is possible to utilize 3D body scanning of CAF personnel to assess fit with soft avatars in operational postures, and suggest several avenues for further research.

Objectifs: L'objectif principal était d'évaluer l'utilisation de modèles de tissus mous pour évaluer l'ajustement des vêtements et de l'équipement de protection sur le personnel féminin des FAC. Les autres objectifs étaient de construire les modèles de tissus mous à partir de scans 3D bruts fournis par RDDC et d'évaluer l'adéquation aux postures opérationnelles.

Résultats:

Implications pour les gilets pareballes féminins: l'étude a montré des conséquences surprenantes pour les changements d'entrefer et de pression maximale avec des changements dans le serrage des sangles et la posture du personnel f éminin. L'étanchéité de la sangle a diminué l'entrefer et également la pression maximale, mais pas de manière uniforme. Des pics de pression ont été observés sur l'épaule et non sur la poitrine, même sur le corps féminin, dans nos simulations. L'emplacement des zones de haute pression sur le corps variait selon la posture, avec des pressions plus importantes observées sur la hanche et le bas du dos pendant la position assise et dans les zones des bras pendant le tir. Ces pressions pourraient entrâiner une gêne, une distraction et pourraient limiter l'amplitude des mouvements. Ces résultats peuvent être utilis és pour évaluer la protection, ainsi que le confort physique et thermique, des gilets pareballes féminins.

Démonstration des capacités techniques: (1) Construction robuste d'avatars logiciels à partir de scans bruts, même en présence d'artefacts de scan importants. (2) Avatars souples posables. Nous avons démontré la capacité de poser et d'enregistrer l'avatar, y compris le modèle FEM des tissus mous, dans trois postures op érationnelles : debout, assis comme à l'arrière d'un transporteur de troupes et tenant les bras leés dans une pose de tir. Ces résultats suggèrent qu'il est possible d'utiliser la numérisation 3D du corps du personnel des FAC pour évaluer l'adéquation avec des avatars souples dans des postures opérationnelles, et suggèrent plusieurs pistes de recherche.